Controlling Environmental Tobacco Smoke in Offices

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A case study on the effectiveness of supplemental air cleaning to control environmental tobacco smoke in a single-level office building

Building engineers, operators, and managers are increasingly required to accommodate both smoking and nonsmoking tenants in the current marketplace. Available options include general dilution ventilation with outside air without separation of smokers and nonsmokers, spatial separation of smokers and nonsmokers, and physical separation of smokers and nonsmokers. Designated smoking and nonsmoking areas may be configured without changes to the HVAC systems, with the addition of supplemental air cleaning technology, or with the addition of auxiliary exhaust systems. Each configuration option affects the capital and operating costs of a building.

A study to assess the effectiveness of supplemental air cleaning to control airborne levels of environmental tobacco smoke (ETS) was conducted in a single-level office building in Redmond, Wash. Three air cleaners were integrated into the HVAC systems serving the offices. Smoking is permitted throughout the offices with the exception of one designated nonsmoking room that is physically separated from the remaining space. The objectives of the research were to assess the effectiveness of the air cleaners in providing acceptable indoor environmental conditions and to determine the impact of the air cleaning equipment on nonsmokers' exposure to ETS in the designated nonsmoking room.

The HVAC system

The offices are divided into two ventilation zones separated by a floor-to-ceiling wall. The dividing wall contains an open doorway, which creates the potential for air movement between the two ventilation zones. The office configuration and ventilation zones are shown in Fig. 1. The designated nonsmoking room is located in the corner of Zone 1.

The two ventilation zones are served by independent air-handling units (AHUs) located on the rooftop. AHU-1 serves Zone 1 and is a 2-ton heat pump with a design total air flow rate of 800 cfm. Zone 2 is served by AHU-2, a 2.5-ton gas pack with a design total air flow of 1000 cfm.

Outside air is drawn into intakes on the side of each AHU and mixed with return air from the occupied space. The mixed air is filtered, tempered, and delivered to the occupied space through ducted rectangular diffusers in the suspended ceiling. Return air is ducted directly back to each AHU, where a portion is mixed with the outside air and the remainder is exhausted to the outside. The mixed air dampers in each unit do not mechanically modulate and are manually positioned. During the test periods, the dampers were positioned to provide approximately 50 percent outside air and 50 percent return air.

The designated nonsmoking room has been configured to be positively pressurized relative to the adjacent smoking-permitted space. Ventilation air is supplied to the room through a ceiling diffuser. There is no return air vent in the suspended ceiling, so room air should move out of the nonsmoking room through the open door or below the closed undercut door.

Air cleaning equipment

Three fan-powered air cleaning units have been integrated into the HVAC system. Two units were added to the system serving Zone 1, and a single unit was added to Zone 2. All three units include three stages of filtration:

◆ A 2-in. multi-density polyester prefilter rated at 88 percent dust-arrestance efficiency for the removal of dust and large particles (all filter efficiencies are based on ASHRAE Standard 52.1-1992[1]).

◆ A high-efficiency particulate air (HEPA) filter rated at 99.97 percent dust-arrestance efficiency for the removal of smoke, dust, bacteria, and other submicron-size particles.

◆ A 2-in. charcoal filter bed for the removal of odors and gases.

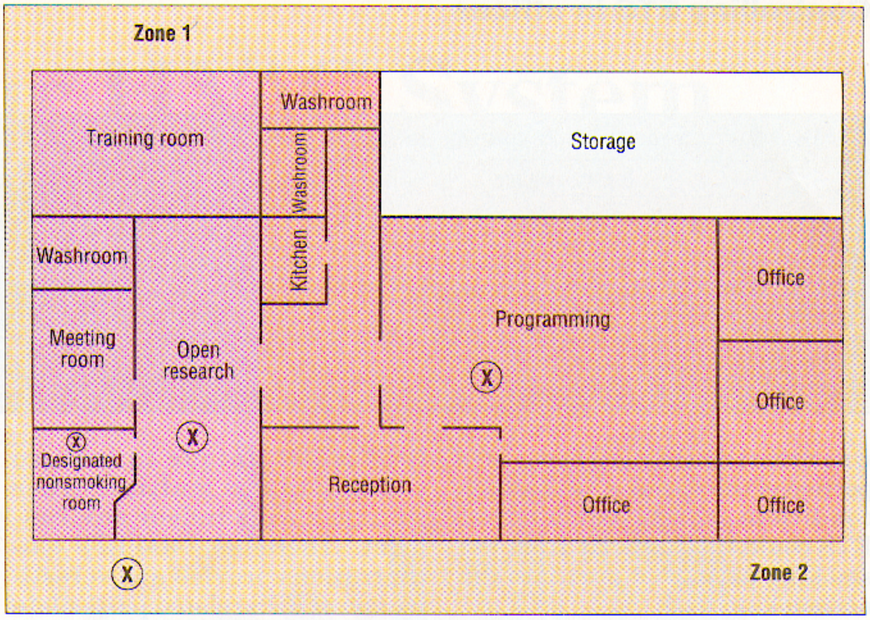
Two-speed fans draw air through the air cleaners. During the research period, the units were operated at the high fan setting with a design air flow of 1000 cfm.

Fig. 2 shows the integrated configuration of the air cleaners into the HVAC systems. In Zone 1, the two duct-mounted air cleaners were installed on the supply air side to clean the mixed outside/return air. In Zone 2, a single air cleaner was installed into the ductwork on the return air side. Therefore, return air from Zone 2 passes through the unit prior to recirculation through the rooftop AHU.

Air quality sampling strategy

Air quality monitoring was simultaneously conducted at three indoor locations and at an outdoor site. The following monitoring locations are each identified by an "X" in Fig. 1:

[1]*Superscript numerals indicate references listed at end of article.*



1 Ventilation zone configuration and sampling site locations.

◆ The "open research" office in Zone 1, in which smoking is permitted without restriction.

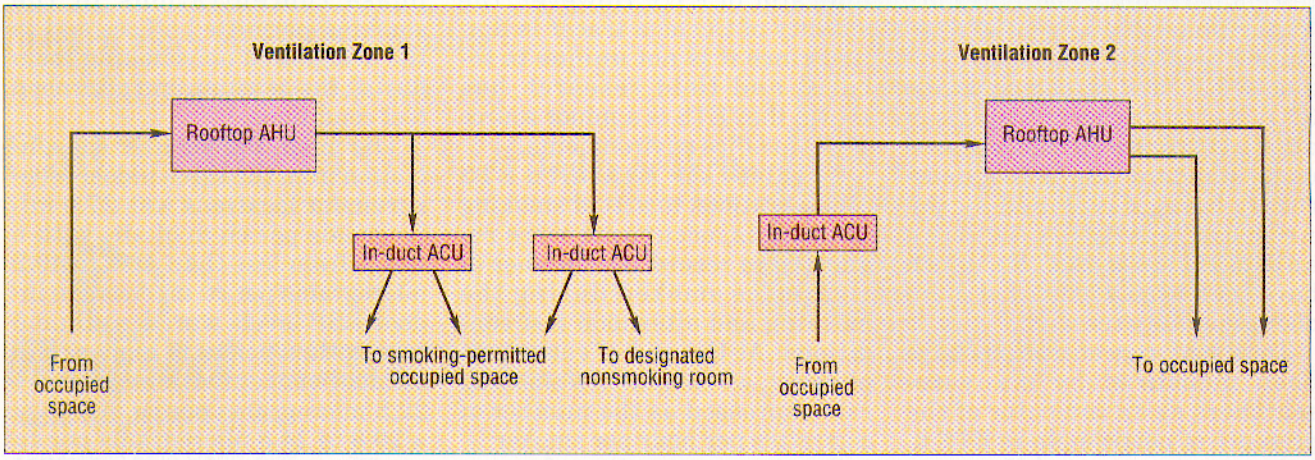
◆ The designated nonsmoking room in Zone 1.

◆ The "programming" office in Zone 2, in which smoking is permitted without restriction.

◆ Outdoors at street level (to provide a baseline of data for comparison with indoor levels).

Data were collected under two varying test conditions, during the morning and afternoon of one workday. During the morning test condition, the door to the nonsmoking room was closed, and smoke pencil analysis showed a strong positive pressurization relative to the adjacent research area as indicated by air flowing out of the nonsmoking room beneath the undercut door. This pattern of air movement should effectively limit the direct migration of ETS from the smoking-permitted offices into the nonsmoking room. Therefore, the presence of ETS in the nonsmoking room would be attributed to recirculation through the HVAC and air cleaning systems.

For the afternoon test condition, the door between the nonsmoking room and adjacent smoking-permitted space was left open. Smoke pencil tests showed a relatively neutral pressure relationship. Observation showed air moving out of the nonsmoking room through the lower portion of the opening. This air flow pattern



2 Diagrams of the integrated configuration of the air cleaners into the HVAC system.

TABLE 1—Summary of air quality measurements—daily means and ranges of values.

	Particle phase			Vapor phase						
	Total RSP, µg/m³	UVPM, µg/m³	FPM, µg/m³	Nicotine, µg/m³	3-EP, µg/m³	CO, ppm	Smoking rate, cigs/hr/person	CO_2, ppm	Temperature, F	Humidity, percent
Mean	27.0	9.7	8.9	2.4	0.9	1.7	1.8	438	75.5	33.4
Range	<12.5-40.2	<2.0-13.1	2.2-15.6	0.2-5.6	<0.4-1.6	0.9-2.0	1.4-2.1	350-590	73.5-76.8	29.0-37.3
Outdoors	22.8	5.4	5.8	—	—	2.8	—	344	53.6	72.3
Range	20.8-24.8	4.9-5.9	5.6-6.1	—	—	1.9-3.5	—	325-350	51.8-56.5	63.1-78.5

was reversed through the upper portion of the opening. Given such conditions, it was feasible that ETS could flow directly from the smoking-permitted area into the nonsmoking room.

Data collection

Data were collected at each monitoring location to assess ETS-related concentrations and HVAC system performance. ETS is a dynamic and complex chemical mixture in air consisting of vapor-phase and particle-phase compounds. Due to the dynamic and unpredictable nature of ETS, one can best characterize an accurate assessment of ETS concentrations in air by simultaneously monitoring selective particle-phase and vapor-phase tracers.[2] Consequently, six phase-selective tracers of ETS were simultaneously determined at each indoor sampling site. The measured tracers of particle-phase ETS included total respirable suspended particles (RSP), ultraviolet particulate matter (UVPM), and fluorescent particulate matter (FPM). Vapor-phase tracers of ETS included nicotine, 3-ethenylpyridine (3-EP), and carbon monoxide (CO). Airborne concentrations of all six tracers were determined using standard test methods currently being developed by the American Society for Testing and Materials (ASTM), which have been widely employed in indoor air quality research.[3]

Total RSP concentrations have been measured by many researchers as an indicator of the presence of particle-phase ETS in indoor environments.[4] However, RSP is not unique to tobacco smoke and has multiple other sources in the indoor environment.[3] Therefore, total RSP concentrations provide an overestimation of ETS-related particulate matter. To provide a better estimate of ETS-related particulate concentrations, we also determined UVPM and FPM concentrations, which reflect concentrations of combustion-generated particulate matter, including ETS.[5]

Nicotine has been widely used in field research as a tracer of vapor-phase ETS because it is unique to ETS. However, chamber experiments have questioned the validity of nicotine as an appropriate indicator due to unpredictable decay kinetics.[2] Therefore, another vapor-phase tracer unique to tobacco smoke, 3-EP, was determined in addition to airborne nicotine. CO concentrations were also monitored as a vapor-phase tracer of ETS since many previous studies of ETS exposure have relied on CO measurements as an indicator of ETS. However, the validity of CO as a tracer is limited since it is not unique to tobacco and field research has shown that ETS is a minor source of CO in office environments.[4]

To relate the measured ETS concentrations to actual smoking conditions, occupants were requested to record the number of cigarettes smoked during the morning and afternoon test conditions. At the end of each sampling set, we computed a smoking rate expressed as the number of cigarettes per hour per smoker.

Continuous monitors for carbon dioxide (CO_2), temperature, and relative humidity were installed at each indoor site to assess air quality and thermal conditions in the study offices with reference to current North American engineering standards. Passive nondispersive infrared (NDIR) continuous analyzers integrated with digital dataloggers, which include sensors to measure all three parameters, were used.

Data development

The results from the ETS monitoring and HVAC system performance evaluation are shown in Table 1 and Figs. 3 and 4. Table 1 presents an overall summary of air quality conditions in the study offices during both test conditions, showing mean ETS-related concentrations and average CO_2 and thermal comfort conditions over the day of measurement. Figs. 3 and 4 examine the impact of the physical separation of smokers and nonsmokers on indoor air quality. Bar graphs compare particle-phase and vapor-phase concentrations in the smoking-permitted offices and in the designated nonsmoking room during the morning and afternoon test conditions.

The mean indoor RSP concentration from the three indoor measurement locations was 27.0 micrograms per cu m of air, with a range from less than 12.5 to 40.2 micrograms per cu m. Average indoor RSP levels were less than 6 micrograms per cu m higher than outdoor concentrations (mean = 22.8 micrograms per cu m, range = 20.8 to 24.8 micrograms per cu m). The results from the UVPM

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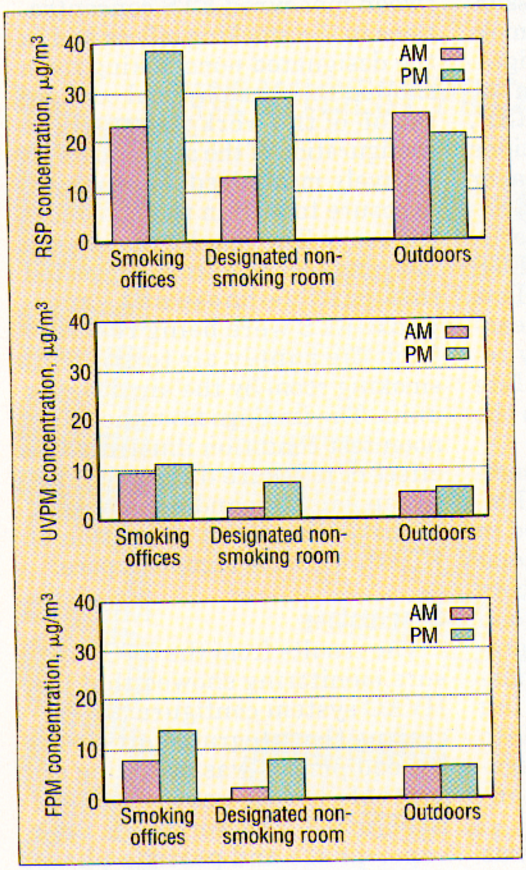
and FPM analyses estimated that between 30 and 40 percent of the total particulate was related to ETS and other combustion byproducts. The analysis of the outdoor air samples also estimated that between 20 and 25 percent of the particulate matter in the outdoor air was attributable to combustion sources, primarily vehicle exhaust.

Occupational exposure regulations for U.S. workplaces do not currently include permissible exposure limits (PEL) for total RSP. However, assessment of the acceptability of the particulate levels in the study offices is possible through comparison with World Health Organization (WHO) air quality guidelines. WHO has identified a "level of limited or no concern" for ETS-related particulate matter of 100 micrograms per cu m and a "level of concern" of greater than 150 micrograms per cu m.[6] The ETS-related particulate concentrations in the study offices were 10 times lower than the WHO level of "limited or no concern" for health and comfort.

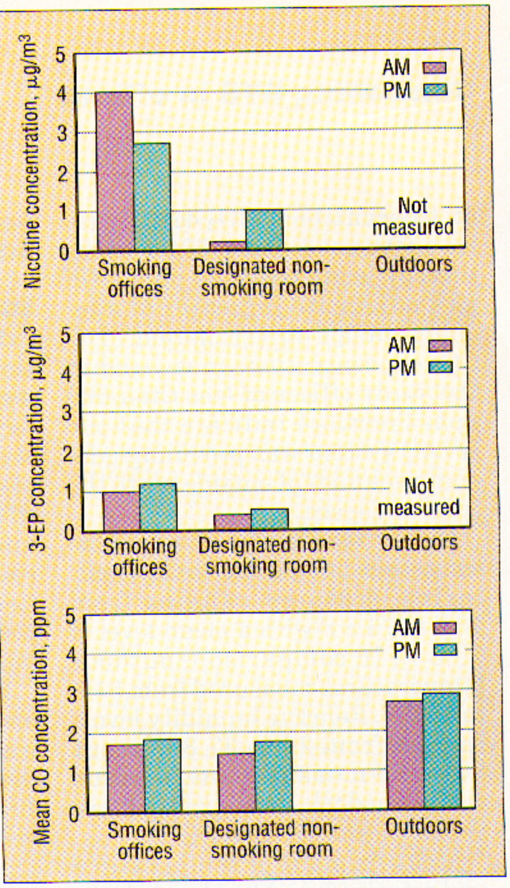
Vapor-phase ETS concentrations were also substantially less than current workplace air quality regulations. The U.S. Occupational Safety and Health Administration (OSHA) has defined a PEL for nicotine of 500 micrograms per cu m (8-hr time-weighted average). Nicotine concentrations throughout the study offices (mean = 2.4 micrograms per cu m, range = 0.2 to 5.6 micrograms per cu m) were 100 times below the OSHA regulatory level for U.S. workplaces. The OSHA PEL for nicotine is also consistent with recommended guidelines for workplace exposure to nicotine published by the American Conference of Governmental Industrial Hygienists (ACGIH) and the U.S. National Institute of Occupational Safety and Health (NIOSH).



3 Particle-phase ETS tracer levels on November 9, 1994.

Such workplace regulations and guidelines have been primarily developed to protect workers from serious health impairment rather than discomfort and irritation. As a rule of thumb, a guideline of one-tenth of the occupational exposure limit has been suggested as the level that "would not produce complaints in a nonindustrial population in residential, office, school, or other similar environments."[7] For nicotine, this guideline would be 50 micrograms per cu m. The nicotine data collected in the study offices were 10 times lower than this rule-of-thumb guideline.

The CO concentrations measured in the study offices were also far below estab-



4 Vapor-phase ETS tracer levels on November 9, 1994.

lished workplace exposure regulations and guidelines. The OSHA PEL for CO is 50 ppm (8-hr time-weighted average). In comparison, CO levels in the study offices ranged from 0.7 to 2.0 ppm.

The overall results from the air quality monitoring clearly show that ETS-related constituents were being effectively controlled to low levels throughout the study offices.

HVAC system performance

CO_2 concentrations ranged from 350 to 590 ppm with a mean concentration of 438 ppm. CO_2 levels were similar at all three indoor monitoring locations during both the morning and afternoon test conditions. In comparison, outdoor CO_2 levels were 325 to 350 ppm.

CO_2 measurements provide an indication of the acceptability of ventilation conditions in buildings. The current North American ventilation standard established by ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality*, describes minimum outside air ventilation rates based on the control of CO_2 concentrations to less than 1000 ppm, thereby using the 1000 ppm level as a surrogate indicator of adequate outside air ventilation.[7] The CO_2 concentrations measured in the study offices of less than 600 ppm therefore indicate that the HVAC system was providing adequate volumes of outside air to the occupied space.

Indoor temperatures were also consistent among the three monitoring locations, ranging from 73.5 to 76.8 F with a mean level of 75.5 F. In comparison, outdoor temperatures measured from 51.8 to 56.5 F. Relative humidity levels ranged from 29 to 37.3 percent over the measurement periods while outdoor levels ranged between 67 and 76 percent.

Measurement of temperature and relative humidity levels indicates the effectiveness of HVAC system performance in providing acceptable thermal conditions within the workplace. ASHRAE Standard 55-1992, *Thermal Environmental Conditions for Human Occupancy*, defines optimal levels and acceptable ranges of indoor temperature and humidity for occupant comfort. For mild climatic conditions, optimal temperature is 76 F with an acceptable range of 73 to 79 F given relative humidity levels between 30 and 35 percent.[8] The temperature levels throughout the study offices were within this acceptable range, indicating effective thermal control by the HVAC system.

ASHRAE Standard 55-1992 also defines an acceptable comfort range for indoor relative humidity of 20 to 60 percent. The humidity levels in the study offices (30 to 35 percent) were within this range and suggest effective thermal control by the HVAC system.

Overall, the findings from the CO_2, temperature, and relative humidity monitoring indicate that the HVAC system serving the study offices was providing acceptable outside air ventilation and appropriate thermal control during the period of evaluation.

Smoking vs. nonsmoking areas

While absolute ETS concentrations throughout the study offices were effectively controlled to levels far below existing workplace regulations and guidelines, comparison of the ETS-related concentrations in the smoking-permitted offices and the designated nonsmoking room during the two test conditions shows that nonsmokers' exposure to ETS can be further minimized by spatial separation.

Fig. 3 compares the measured levels of the three particle-phase tracers in the smoking offices and the designated nonsmoking room during the morning and afternoon test conditions. The results show consistently lower RSP, UVPM, and FPM concentrations in the nonsmoking room. During the morning test condition, when the closed door and positive pressurization of the designated nonsmoking room prevented direct migration of ETS into the room from the adjacent smoking areas, RSP, UVPM, and FPM concentrations in the nonsmoking room were at or below the limits of analytical detection, indicating minimal recirculation of particle-phase ETS through the HVAC system. This result suggests that the air cleaning systems were effectively removing ETS-related particulate matter from the supply air to the nonsmoking room.

During the afternoon test condition, slightly higher RSP, UVPM, and FPM levels were observed in the nonsmoking room. The comparably higher ETS-related constituents during the afternoon may be attributed to direct migration of diluted air from the smoking offices to the nonsmoking room through the open door due to the near neutral or slightly negative pressurization of the nonsmoking room.

A similar pattern of results was also observed for the vapor-phase tracers of ETS, as shown in Fig. 4. During the morning test condition, nicotine and 3-EP concentrations in the nonsmoking room were at or below detectable levels, indicating that the air cleaning units were effectively filtering the two vapor-phase tracers unique to tobacco smoke in the air being supplied to the designated nonsmoking room. CO concentrations were similar in the smoking and nonsmoking locations. However, as previously noted, CO is not a good indicator of ETS exposure as there are multiple sources in indoor and outdoor environments.

During the afternoon test condition, nicotine and 3-EP concentrations were slightly higher in the designated nonsmoking room, resulting from the direct flow of air from the smoking areas into the nonsmoking room through the open door due to the slightly negative pressurization of the room.

Overall, the comparison between measured ETS concentrations in the smoking offices and in the designated nonsmoking room showed that the physical configuration of the workplace and the configuration of the air cleaners effectively minimized nonsmokers' exposure to ETS in the nonsmoking room. The results during the morning test condition suggested that particle-phase and vapor-phase ETS were being removed from the supply air to the nonsmoking room by the air cleaning units. The findings from the afternoon test condition illustrate the effect of pressure differences between smoking and nonsmoking areas on the direct migration of ETS through the occupied space.

Conclusions

The results from the ETS exposure monitoring showed that the HVAC system configuration (including the integrated air cleaning equipment) was providing acceptable indoor environmental conditions in the workplace. Both vapor-phase and particle-phase components of ETS were controlled to low levels in the presence of smoking in the office areas and were further reduced in the designated nonsmoking room.

The nicotine concentrations throughout the study offices were more than 100 times lower than the current U.S. workplace exposure regulations administered by OSHA. ETS-related particulate concentrations were also less than levels considered to be "of limited or no concern" for health and comfort by the World Health Organization.

The effective control of ETS to low levels in the study office was achieved through a combination of dilution ventilation and application of air cleaning technology. The HVAC system was supplying adequate volumes of outside air to the space (as indicated by the measured CO_2 concentrations), and the air cleaners were removing ETS constituents from the ventilation air.

These research findings suggest that rather than prohibiting smoking indoors, building operators have options available to accommodate both smokers and nonsmokers in their buildings. This case study indicates that dilution ventilation and application of air cleaning technology provide practical alternatives that can be implemented to control ETS effectively in the workplace. **HPAC**

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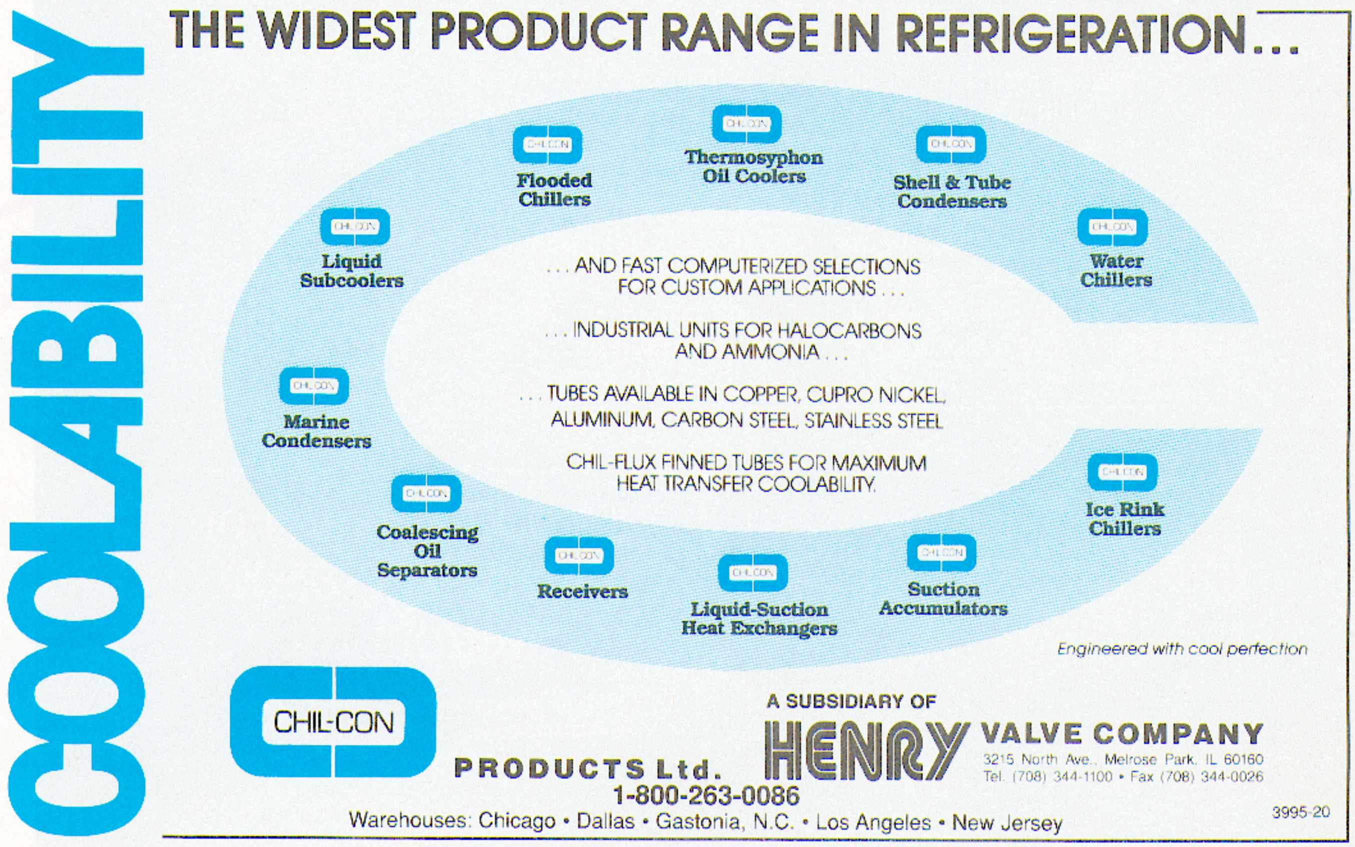

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